Pope and Potter

Polyphase Motors on Unbalanced Systems

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POLYPHASE MOTORS ON UNBALANCED SYSTEMS

BY

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June 1, 1909

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

CHARLES SAMUEL POPE and CHARLES PRUITT POTTER

ENTITLED POLYPHASE MOTORS ON UNBALANCED SYSTEMS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

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Instructor in Charge

APPROVED: Morgan Brooks.

HEAD OF DEPARTMENT OF Electrical Engineering

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Introduction.

In all systems of electrical distribution, employing more than one phase for the transmission of power, it is generally the aim of the operator to so adjust the load that it will be the same, or very nearly so, on each of the different phases. Since this is the object in view, due care should be exercised in designing and balancing the system. There are however, cases where it is impossible to accomplish this end, or where only an approximate balance is required. At the same time it must be taken into consideration that an amount of unbalance which would be negligible in a large machine, would affect very materially the behavior and efficiency of a smaller unit. It is the behavior and effect of polyphase motors, both of the induction and synchronous type, when running on one of these unbalanced systems, that we have undertaken to investigate and report on in this thesis.

While this investigation is in part the same as that carried on by Messrs. Crosset and Hall in the thesis which they presented in 1908, and may overlap their work in parts, it is taken up from a somewhat different standpoint in many respects, being in the nature of a continuation of their tests.

It was the original intention to make the "balancing effect" the principal point of investigation, but it was later decided to make a more or less general test on the motors under investiga-

tion. It will therefore be our aim in the following report to show the effect of the motor load on the voltage and power of the different phases, and also the effects of the unbalanced source of supply on the efficiency, power factor and speed of the motor itself.

Theory:-

Two general classes of motors were dealt with in this thesis,- viz. induction and synchronous motors. A general summary of the theory of the two machines follows.

The induction motor consists primarily of two parts, one generally called the stator, to which polyphase currents are supplied, and the other known as the rotor, consisting of short-circuited windings wound on a shaft. The windings of the stator are exactly similar to the armature winding of an alternator, and when supplied with alternating currents in the proper phase relations, produce a rotating field. This rotating magnetism induces currents in the rotor which react on the magnetism causing the rotor to move. The rotor tends to revolve at synchronous speed, that is, at a speed common with that of the rotating magnetism. The rotor never quite reaches synchronous speed for this reason: in order that currents be induced in the rotor, its conductors must cut lines of force. If however, the revolving part has the same speed as the rotating magnetism, no lines of force will be cut, and there will be no force tending to produce rotation. Consequently, the rotor falls behind the rotating field, and has a certain

definite slip just sufficient to produce the currents necessary for its propulsion. As the motor is loaded, the slip becomes greater and greater, and if the load becomes excessive the machine will slow down and come to rest, the slip becoming 100 %.

If the rotor resistance is doubled and the relative speed of the stator magnetism and rotor is doubled, the electromotive forces induced in the rotor windings are doubled, the rotor currents remain the same and the torque is the same as before. It is therefore desirable to provide an induction motor starting under load with a rotor having an adjustable resistance so as to produce large torque at starting. The motor used was of this type, but the tests run on it were all taken with the adjustable resistance short circuited.

It is well known that if one phase of a polyphase motor be disconnected from the supply circuit, that the motor will then operate on the remaining phases and supply a voltage somewhat less than the supply voltage on the open phase. Part of the machine will then be operating as a generator and part as a motor. In the same way, if the voltage on one phase is lower than that on the others, before the motor is thrown on the line, the low voltage will be increased and the others decreased as soon as the motor is started, the motor acting as a motor-generator. It is the purpose of this thesis to investigate this action, as to the balancing of voltage, and furthermore to load the low voltage phase with lamps and discover whether or not there is a balancing of power. This is a condition similar to that obtained in actual

practice, for the heavy loaded phase of a polyphase system is naturally the low voltage phase due to the IR drop in the line being excessive on the heavier loaded side.

The synchronous motor is exactly like a synchronous generator, and its operation is similar to that of a generator running in parallel with another, the only difference being that in the case of the motor the driving force becomes negative, and the machine receives power instead of supplying it. Running in this way the machine may be used as a motor having considerably higher efficiency and power factor than the induction motor. The disadvantage of the synchronous motor is that it must be brought up to synchronous speed from an exterior source and synchronized with its generator. Its advantage lies in the fact that it has a constant speed up to its full load. The induction motor is superior to the synchronous motor in that it has no moving contacts and is practically fool-proof due to its robust construction.

Like the induction motor, the synchronous motor can run single phase and voltage and power taken from the open phases. Because of the fact that the synchronous machine acts equally well as a motor or generator, it should exhibit better balancing characteristics than the induction machine. It is true, that the induction machine will act as a generator under the proper conditions, but those conditions are special and rather hard to meet. For instance, to act as a true generator, the induction machine must be driven above synchronous speed and must have a leading

current supplied to it from an outside source. The synchronous machine however will act as a generator under almost any conditions and should therefore be more satisfactory for this test than the induction machine.

The problem came up as to how to obtain an unbalanced system corresponding to that obtained in actual practice. Previous work done in this line had been done with the unbalance produced by the insertion of a heavy resistance in one phase. This produced an excessive drop in that phase, thus unbalancing the system. In this thesis it was decided to produce the unbalance in a slightly different manner. The addition of resistance would necessarily change the phase the phase relations in the low voltage side. If a transformer were available with different voltage taps this abnormal condition could be avoided and the test carried on in a way corresponding to actual practice. A variable voltage transformer was available and was used for the test.

Diagram of Connections:-

On the following pages are shown diagrams of the connections used, Fig. 1 being the set up used for the induction machine, and Fig. 2 that used for the synchronous machine. The following abbreviations are used. Va and Vb for the voltmeters in the phases A and B, Ia and Ib for the corresponding ammeters, and Wa and Wb for the corresponding wattmeters. Vx and Ix represent the voltmeter and ammeter used in the circuit of the direct durrent machine which supplied the load.

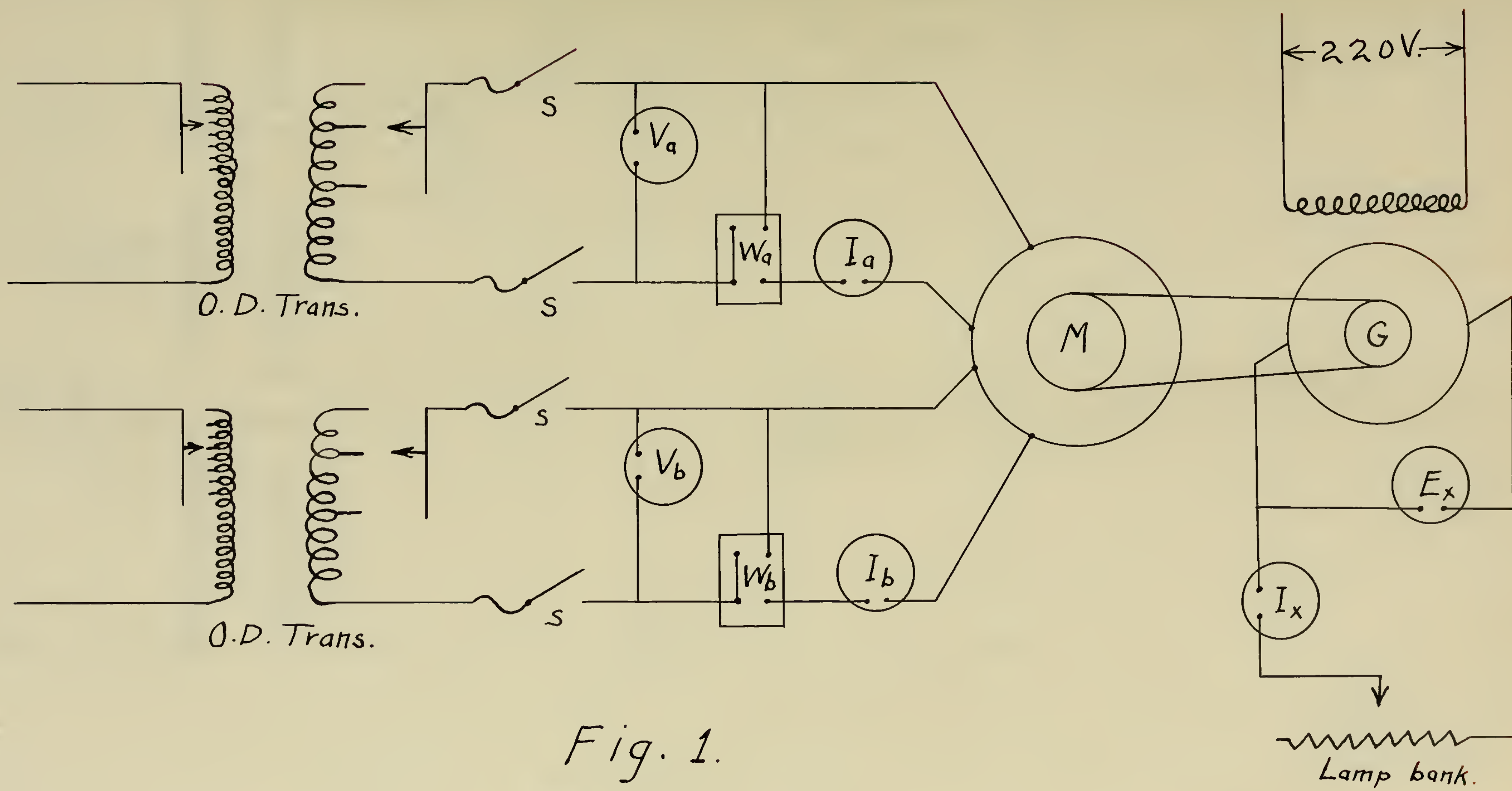


Fig. 1.

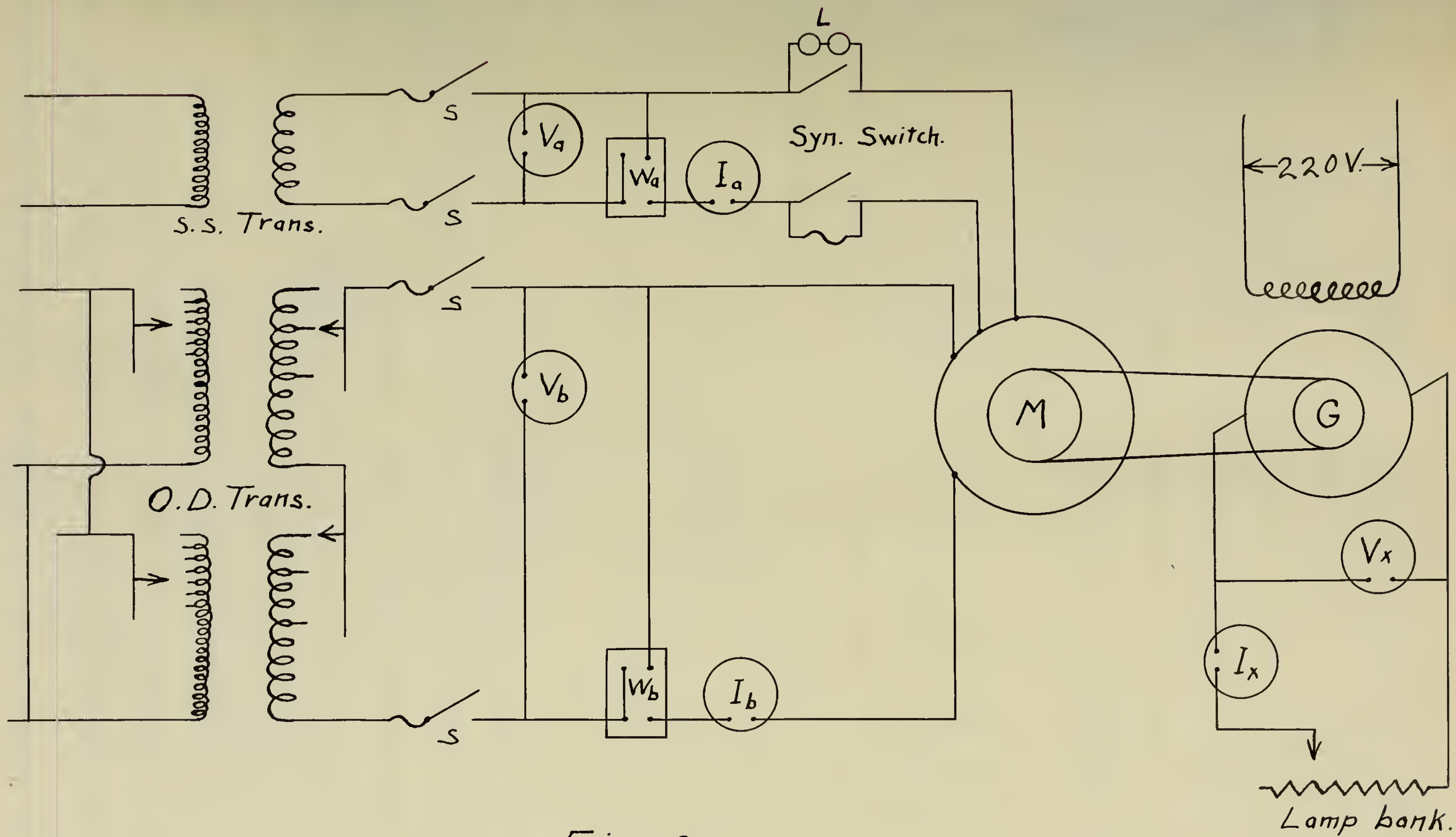

L
Syn. Switch.
220V.
S.S. Trans.
O.D. Trans.
S
S
S
S
V_a
W_a
I_a
V_b
W_b
I_b
M
G
V_x
I_x
Lamp bank.

Fig. 2.

Method of Making Tests:-

The first tests were run on the induction motor. The machine used was a 5 H. P. Westinghouse, Type F, variable speed crane motor. The stator had two phase windings for 110 volts, the rotor was wound and taps brought out to a grid resistance controller. The synchronous speed of the machine was 1200 R. P. M. at 60 cycles. The controller was used merely for starting, all tests being run with the resistance short circuited.

The induction motor was connected up as shown in Fig. 1. The motor was belted to a direct current generator for obtaining the power output. This machine was a Bullock, 220 volt, 15 H. P. machine running at 1100 R. P. M. The shunt winding of this machine was separately excited from the 220 volt mains of the power plant. The armature circuit was connected to two lamp banks in series, and a voltmeter and ammeter in the circuit measured the output. To obtain the total input of this generator, which is of course the output of the motor, its losses were determined and added to the electrical output measured. To do this the curve was drawn on Plate 1, showing the constant losses, friction, windage, etc. and the variable losses, the heat loss in the armature windings, added, to make the total losses. Three curves were drawn, for 900, 1000, and 1100 R. P. M. and the losses at intermediate speeds obtained by interpolation. Thus to obtain the generator input or motor output, the losses corresponding to the speed and armature current were taken directly from the curves and added to the meas-

ured generator output.

In order to obtain the unbalanced condition in the two phases, the two Westinghouse, 7 1/2 K. W. , 440-110 volt, O. D. transformers with the accompanying regulators, were used. These are shown diagrammatically in the diagram of connections. The primary circuits have taps from various points on the windings, coming out to heavy lugs on a dial, and by means of a sliding contact the number of turns in the primary winding could be changed at will, within the limits of the apparatus. The secondary windings have taps at either end, one at the middle points, and one at the .866 points of their windings brought out to two switchboards. Furthermore either 330, 440 or 550 volts may be impressed upon either primary by connecting the primary and secondary of the sub-station transformers in series, either cumulatively or differentially. It will be readily seen that with these conditions almost any desired voltage may be obtained from about 140 down.

The first test was run balanced, with approximately 110 volts on each phase. This was obtained by using the straight 440 to 110 volt connections on the transformers. Readings were taken on the instruments shown, of current and voltage on the direct current generator, speed of same, and current, voltage and power in each phase of the motor, for different loads from zero to a little over full load. After this, similar tests were run, with one phase at 110 volts, and the other at some lower value, varying down to about 50% unbalance.

From the readings obtained the difference in voltage, power factor in each phase, difference in power, power input, output, and the efficiency of the motor were calculated for each reading. Curves were then drawn between efficiency and output for the various percentages of unbalance. The same was done plotting power factor in each phase against output, for different percentages of unbalance. From these curves, others were taken between efficiency and per cent of unbalance, for different loads. This was done by taking some output and from the first curves plotted, determining the efficiency at various percentages of unbalance. Curves were obtained in the same manner for the power factor in each phase plotted against per cent of unbalance. These curves are shown in plates 5 to 7 inclusive. The curve shown in plate 2 was also drawn between volts difference in the two phases and output. In a similar way the curve in plate 3 was drawn between watts difference and output. This was drawn for the data taken when the low voltage side was paralleled with a non-inductive load. The curve shown in plate 4 was drawn between slip and percent unbalance.

Forthe synchronous motor tests a General Electric alternator was used. This was a two phase, type A. H. B. , 7 1/2 K. W., 220 volt machine, running at 1200 R. P. M. for 60 cycles frequency. Its windings are so arranged that they may be connected for either 1, 2 or 3 phase current, but in this test the two phase connections were used entirely. This motor was belted to the direct current generator and its output obtained in exactly the same way as in the induction motor tests.

To obtain the 220 volts for the synchronous machine, one phase was connected directly to the secondary of one of the substation transformers. For the other phase, the primaries of the two O. D. transformers were in parallel on the other phase of the power plant, and the secondaries were connected in series. The connections are shown in Fig. 2. By means of the secondary taps, and the regulator, almost any voltage from 220 down was obtainable

The direct current machine was used as a motor in starting, the alternator running as a generator. The alternator was then synchronized on phase A, by means of the synchronizing switch and lamps shown in the diagram. The phase relations of the other phase were then tested out, and when found normal the switch on phase B was closed. The driving power was then removed from the motor and it was used as before.

A set of tests was made very similar to the induction motor tests, taking the same readings and making the same calculations. The curves were plotted in exactly the same way as before. Plate 8 shows a graph between volts difference and output, and plate 9 between watts difference and output as before. Plates 10 to 14 show curves between efficiency and power factor in eac phase and per cent of unbalance, plotted for various outputs. The curve between slip and per cent of unbalance could not be duplicated in the synchronous motor tests, because the synchronous motor necessarily runs at synchronous speed. The data taken is tabulated in the following tables and gives thefigures from which the first curves were plotted.

Table 1a gives the data taken for the induction motor with the voltages unbalanced, and the low voltage side loaded with a lamp load, the lamps being so connected that the current and power in them was read by the instruments, an arrangement being made to get the input of the lamps with the motor off. The data given in table 1 was taken with the voltages unbalanced, no load except the motor being on the system. In this test special attention was given to the voltmeter readings, and the readings taken were corrected from a calibration curve.

Table 2a gives the data taken for the synchronous machine with the voltages unbalanced, and the low voltage side loaded with a lamp load, the lamps being connected as before so that their input was included with that of the motor. The data taken for the voltages unbalanced without any lamp load on either phase is shown in table 2.

Observed Data --- Table 1.

Induction Motor.

Ea volts.	Ia amperes.	Pa K. W.	Eb volts.	Ib amperes.	Pb K. W.
110.9	17.0	.91	109.5	15.1	1.06
110.4	20.6	1.48	109.0	20.1	1.65
109.8	26.0	2.13	108.0	25.7	2.24
109.3	30.7	2.63	107.0	31.0	2.75
109.0	34.2	2.99	106.8	35.1	3.08
107.7	38.7	3.18	106.1	38.9	3.38
		9% Unbalanced.			
111.5	0.0	0.0	101.2	0.0	0.0
111.5	20.0	1.0	103.4	10.0	.4
111.5	21.2	1.35	103.2	12.0	.75
111.5	24.0	1.60	102.7	16.0	1.0
111.5	26.0	1.90	102.7	19.0	1.25
111.5	27.6	2.10	102.6	21.0	1.45
111.5	29.4	2.35	102.7	23.0	1.65
111.5	33.6	2.85	102.7	29.0	2.15
111.5	37.6	3.25	102.2	31.5	2.45
111.5	41.6	3.60	102.2	34.5	2.80
		16% Unbalanced.			
111.5	0/0	0.0	93.5	0.0	0.0
111.5	21.0	1.25	94.5	10.0	.25
111.5	26.0	1.60	95.0	15.0	.63
111.5	28.0	1.90	95.0	17.0	.90

16% Unbalanced Continued. Table 1.

Ea volts.	Ia amperes.	Pa K. W.	Eb volts.	Ib amperes.	Pb K.W.
111.5	30.0	2.2	95.0	18.0	1.10
111.5	32.1	2.50	94.5	20/6	1.35
111.5	34.0	2.75	94.5	22.3	1.55
111.5	36.9	3.05	94.0	25.9	1.85
111.5	41.1	3.50	94.5	30.2	2.25
111.5	43.7	3.80	95.0	33.6	2.55
		25% Unbalanced.			
111.5	0.0	0.0	85.3	0.0	0.0
111.5	27.0	1.60	84.7	0.0	.10
111.5	30.0	2.0	85.2	9.0	.45
111.5	32.0	2.25	84.7	14.0	.70
111.5	34.8	2.60	84.5	17.0	.85
111.5	37.2	2.95	84.2	19.0	1.10
111.5	38.0	3.20	84.2	21.0	1.25
111.5	41.5	3.35	84.0	24.0	1.55
111.5	46.5	3.90	83.7	28.4	1.85
		35% Unbalanced.			
111.5	0.0	0.0	72.7	0.0	0.0
111.5	30.0	1.35	74.8	2.6	-.05
111.5	32.4	2.30	74.8	4.1	.20
111.5	35.1	2.70	74.8	7.0	.43
111.5	37.2	2.90	74.6	9.5	.60
111.5	41.5	3.40	74.3	14.0	.90

35% Unbalanced Continued. Table 1.

Ea volts.	Ia amperes.	Pa K. W.	Eb volts.	Ib amperes.	Pb K. W.
111.5	45.2	3.70	74.3	20,6	1.12
111.5	47.8	4.0	74.0	23.5	1.30
		48% Unbalanced.			
111.5	0.0	0.0	57.2	0.0	0.0
111.5	35.1	2.55	60.4	7.0	-.1
111.5	38.7	2.95	60.2	6.5	.05
111.5	39.8	3.05	60.4	6.5	.15
111.5	42.4	3.35	61.0	8.0	.30
111.5	44.7	3.60	60.4	9.5	.45
111.5	50.7	4.15	59.8	13.0	.70

Calculated Data - Table 1.

Induction Motor.

Cos θa	Cos θb	Input K.W.	Output K.W.	Efficiency.	% Slip.
.483	.641	1.97	.90	45.6	5.33
.652	.753	3.13	1.83	58.3	8.60
.747	.806	4.37	2.62	60.0	12.7
.783	.829	5.38	3.14	58.3	17.1
.803	.821	6.07	3.46	57.0	20.8
.805	.819	6.56	3.68	56.1	24.2
		9% Unbalanced.			
---	---	0.0	0.0	---	
.448	.386	1.5	.89	63.5	
.570	.605	2.1	1.26	60.2	
.596	.508	2.6	1.67	64.2	
.655	.640	3.15	2.0	63.5	
.682	.673	3.55	2.28	64.2	
.716	.700	4.00	2.55	63.8	
.761	.723	5.00	3.02	60.3	
.778	.763	5.70	3.30	58.0	
.776	.796	6.40	3.55	55.5	
		16% Unbalanced.			
---	---	0.0	0.0	---	
.533	.265	1.50	.89	59.3	
.551	.442	2.23	1.30	58.0	
.609	.556	2.80	1.67	59.6	

16% Unbalanced Continued. Table 1.

Cos θa	Cos θb	Input K.W.	Output K.W.	Efficiency.
.658	.642	3.30	2.0	60.6
.698	.694	3.85	2.33	60.6
.725	.719	4.30	2.57	59.8
.741	.760	4.90	2.88	58.8
.765	.790	5.75	3.15	54.8
.780	.800	6.35	3.32	52.3
		25% Unbalanced.		
---	---	0.0	0.0	---
.531	.000	1.70	.89	52.3
.598	.587	2.45	1.27	52.0
.630	.591	2.95	1.67	56.6
.670	.592	3.45	2.05	59.4
.710	.688	4.05	2.30	56.8
.755	.706	4.45	2.54	57.1
.766	.768	4.90	2.77	56.5
.751	.780	5.75	3.10	52.3
		35% Unbalanced.		
---	---	0.0	0.0	---
.403	.256	1.30	.89	48.5
.636	.652	2.50	1.26	50,5
.690	.821	3.13	1.67	53.4
.700	.845	3.50	1.96	56.0
.733	.865	4.30	2.29	53.2

35% Unbalanced Continued. Table 1.

Cos θa	Cos θb	Input K.W.	Output K.W.	Efficiency.
.735	.730	4.82	2.51	52.1
.751	.748	5.30	2.62	49.4
		48% Unbalanced.		
---	---	0.0	0.0	---
.652	.236	2.45	.89	36.2
.684	.128	3.00	1.10	36.7
.688	.382	3.20	1.30	40.5
.709	.603	3.65	1.57	43.0
.722	.785	4.05	1.77	43.6
.754	.900	4.85	2.01	41.5

Observed Data --- Table 1a.

Induction Motor.

Ea volts.	Ia amperes.	Pa K.W.	Eb volts.	Ib amperes.	Pb K.W.
115.0	0.0	0.0	97.5	14.0	1.35
114.0	16.0	1.05	97.5	18.5	1.55
111.5	23.0	1.75	96.5	25.0	2.28
111.5	26.0	2.10	93.0	28.0	2.45
112.0	29.2	2.45	94.0	32.5	2.85
110.5	34.0	2.90	90.5	37.0	3.20
105.0	41.5	3.30	89.5	44.0	3.60
		23% Unbalanced.			
109.0	0.0	0.0	83.5	12.0	.97
109.5	19.0	1.50	83.0	13.0	.97
110.5	24.0	1.70	83.5	16.0	1.30
110.0	27.5	2.05	82.0	20.0	1.60
109.0	31.5	2.50	81.5	24.0	1.85
108.5	33.0	2.60	80.0	25.0	2.10
106.5	37.0	2.75	79.0	28.0	2.20
		36% Unbalanced.			
109.0	0.0	0.0	69.0	10.0	.65
108.0	26.0	1.65	70.0	10.0	.60
108.0	29.0	2.00	69.5	13.0	0.80
107.5	33.0	2.45	69.5	16.0	1.10
106.5	37.0	2.85	68.0	20.0	1.35
106.5	40.5	3.07	67.0	23.0	1.55
106.0	42.5	3.23	64.0	25.0	1.60

48% Unbalanced.

110.5	0.0	0.0	57.0	8.0	.42
109.0	31.5	2.07	57.5	8.0	.20
107.0	34.5	2.30	56.0	10.0	.45
105.5	40.0	2.90	55.0	12.5	.70
104.0	46.0	3.35	54.0	18.0	.95
102.5	50.0	3.60	52.5	25.0	1.20

Calculated Data - Table 1a.

Induction Motor.

Output K.W.	Pb - Pa	R. P. M.	% Slip.
0.0	1.35	0	---
0.0	.50	1160	3.3
1.34	.53	1120	6.7
1.92	.35	1040	13.3
2.40	.40	1020	15.0
2.72	.30	940	21.7
3.00	.30	860	28.4
		23% Unbalanced.	
0.0	.97	0	---
0.0	-.53	1180	1.8
.60	-.40	1120	6.7
1.21	-.45	1080	10.0
1.78	-.65	1040	
2.08	-.50	1035	13.8
2.37	-.55	1030	14.1
		36% Unbalanced.	
0.0	.65	0	---
0.0	-1.05	1180	1.8
.60	-1.20	1120	6.7
1.18	-1.35	1050	12.6
1.75	-1.50	1020	15.0
1.94	-1.52	965	19.7
2.10	-1.63	910	24.2

48% Unbalanced.

0.0	.42	0	---
0.0	-1.87	1120	6.7
.56	-1.85	1060	11.6
1.15	-2.20	1020	15.0
1.56	-2.50	910	24.2
1.79	-2.40	740	38.4

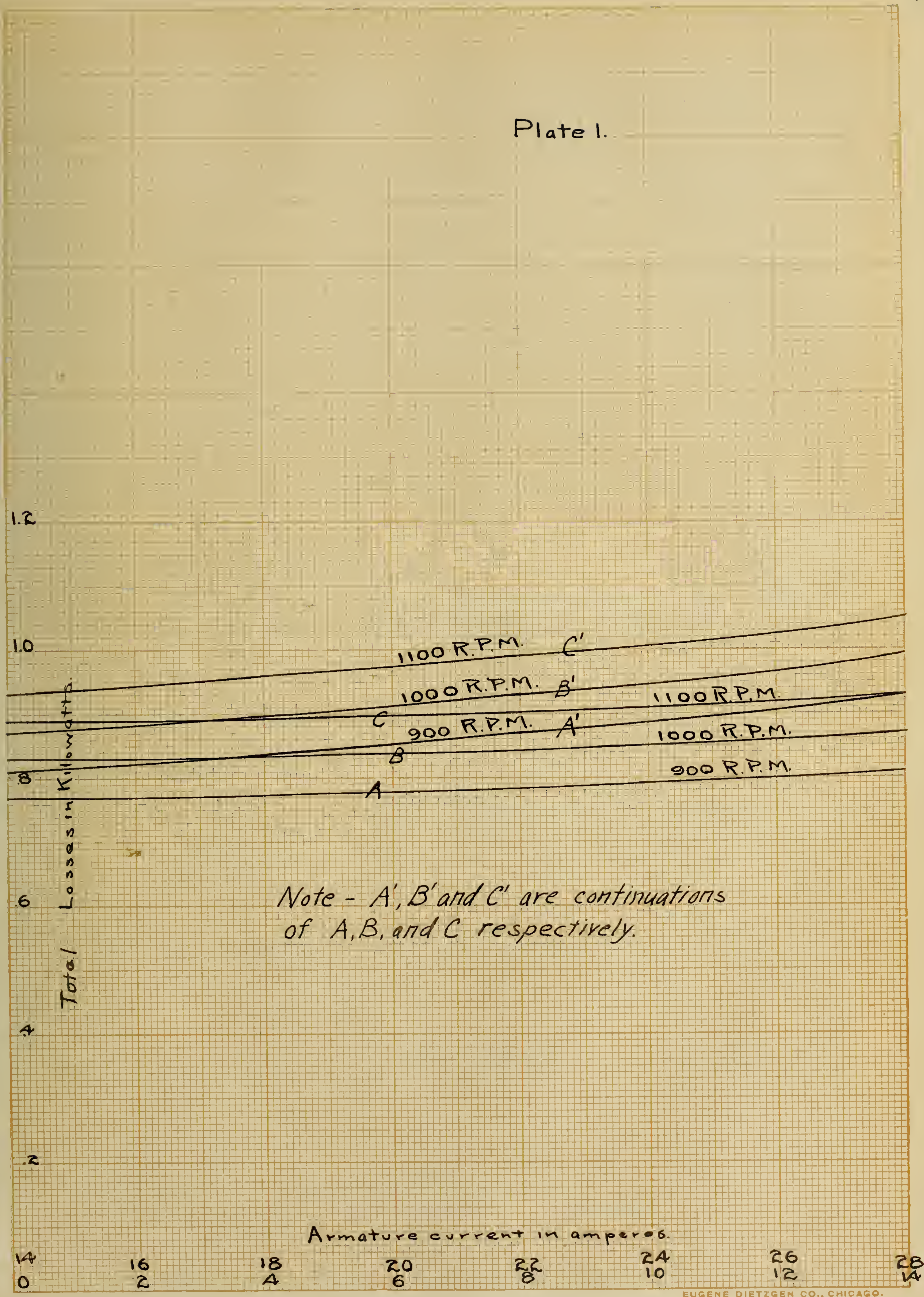
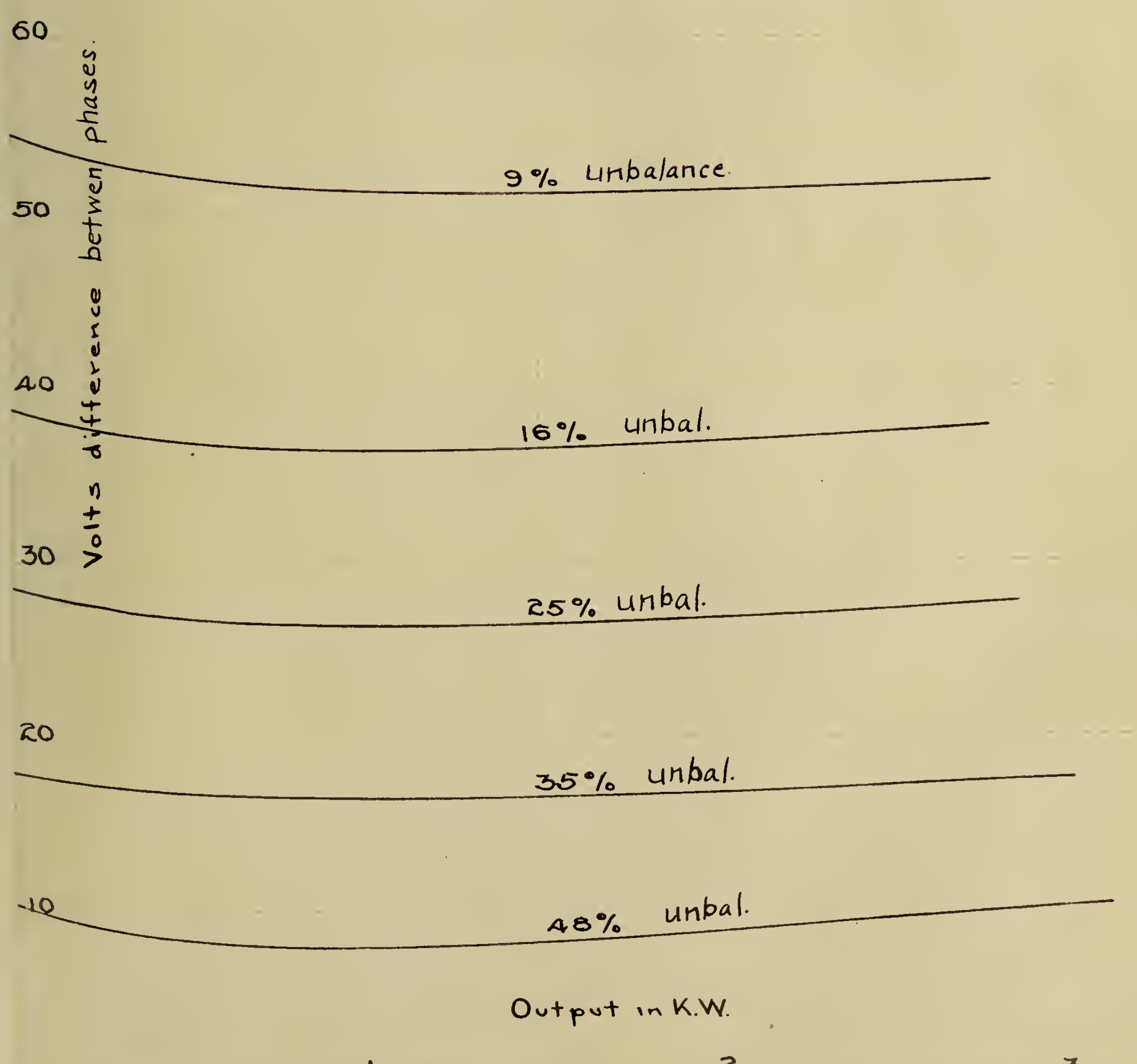


Plate 1.
1.2
1.0
.8
.6
.4
.2
Total Losses in Kilowatts.
1100 R.P.M. C'
1000 R.P.M. B'
900 R.P.M. A'
C
B
A
1100 R.P.M.
1000 R.P.M.
900 R.P.M.
Note - A', B' and C' are continuations of A, B, and C respectively.
Armature current in amperes.
14 16 18 20 22 24 26 28
0 2 4 6 8 10 12 14
EUGENE DIETZGEN CO., CHICAGO.

Plate 2


60
50
40
30
20
10
Volts difference betwen phases.
9% unbalance
16% unbal.
25% unbal.
35% unbal.
48% unbal.
Output in K.W.
1
2
3

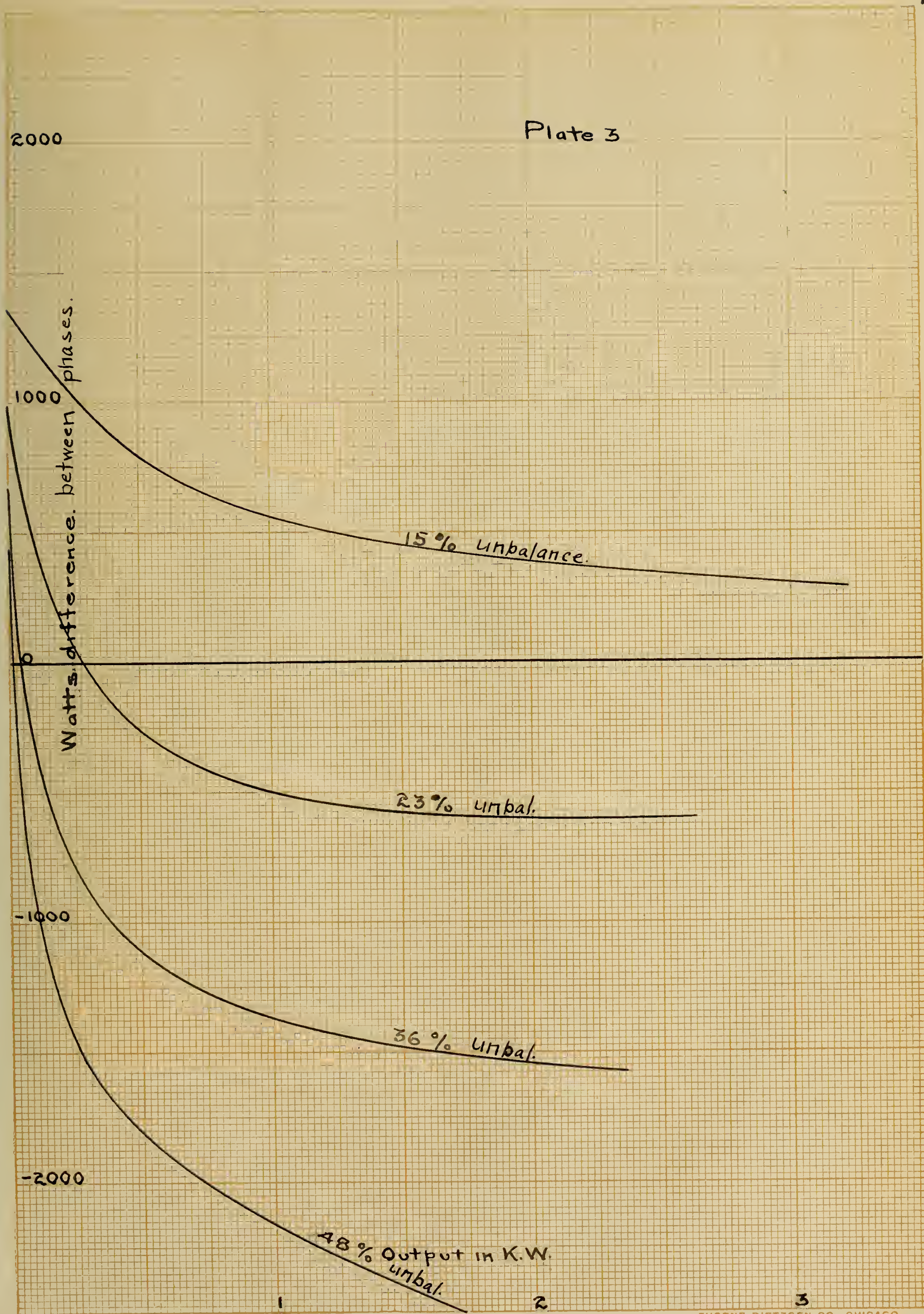
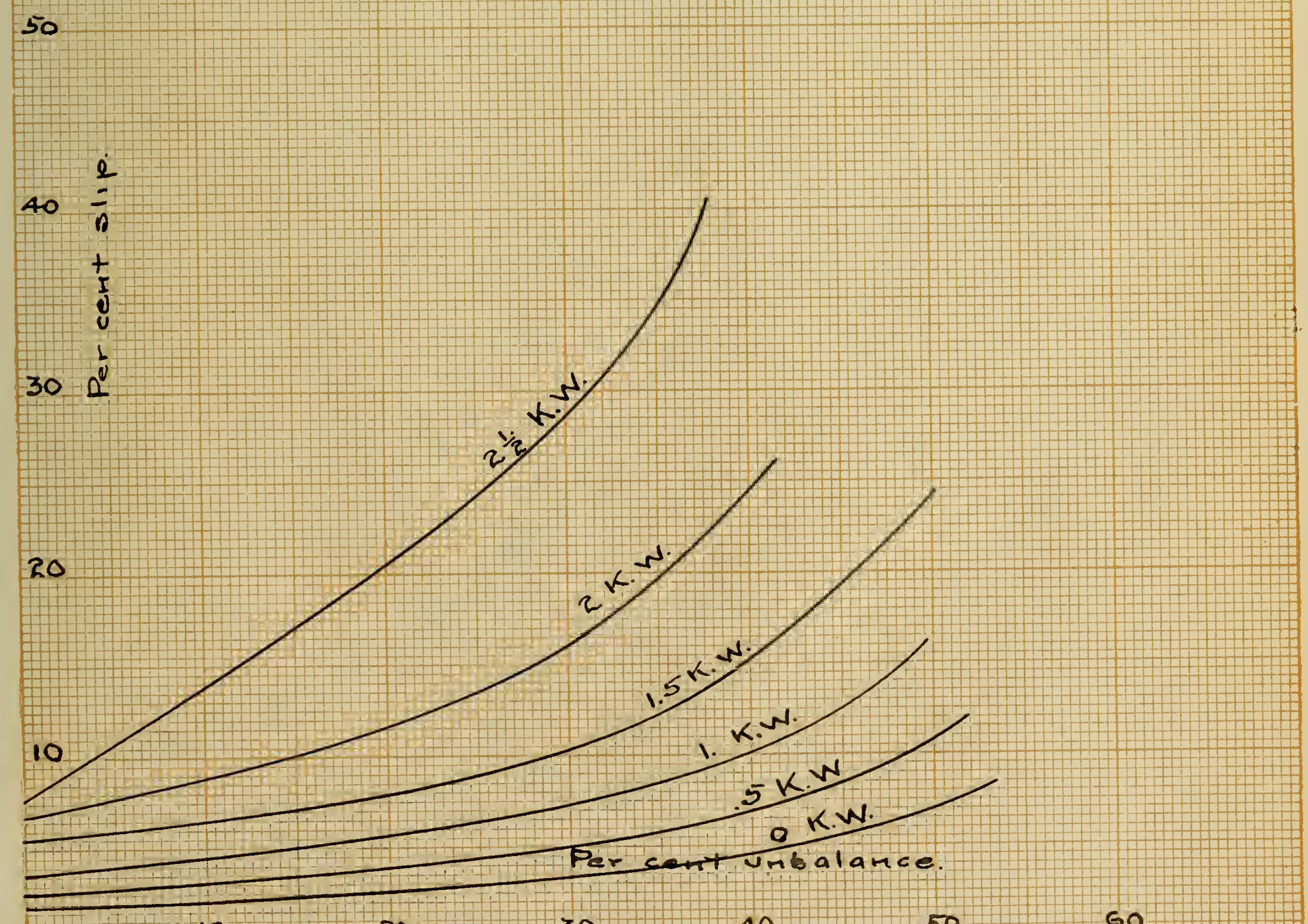


Plate 3
2000
1000
0
-1000
-2000
Watts difference between phases.
15% unbalance.
23% unbal.
36% unbal.
48% unbal.
Output in K.W.
1
2
3
EUGENE DIETZGEN CO., CHICAGO.

Plate 4.



50
40
30
20
10
Per cent slip.
2½ K.W.
2 K.W.
1.5 K.W.
1. K.W.
.5 K.W
0 K.W.
Per cent unbalance.
10
20
30
40
50
60

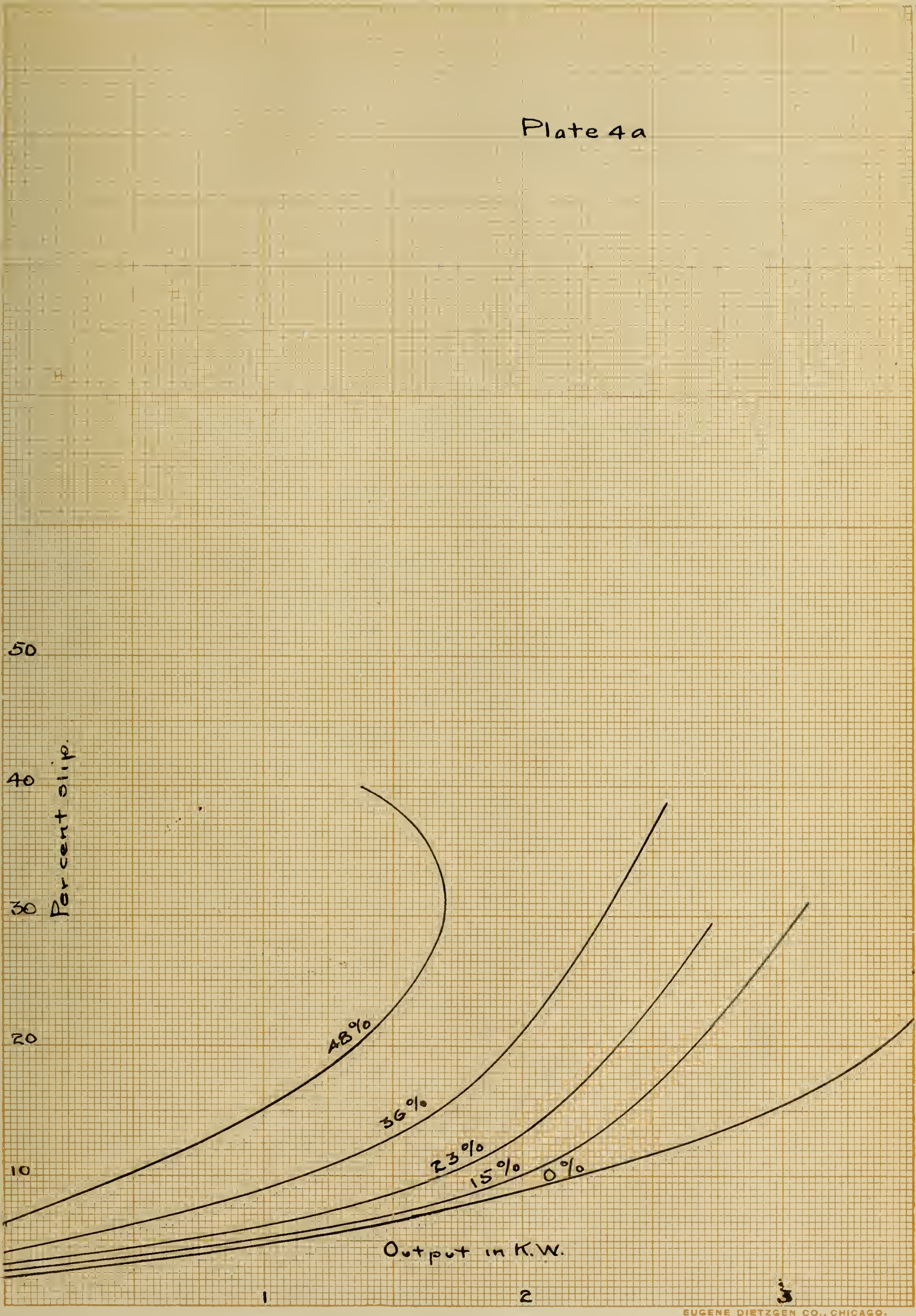
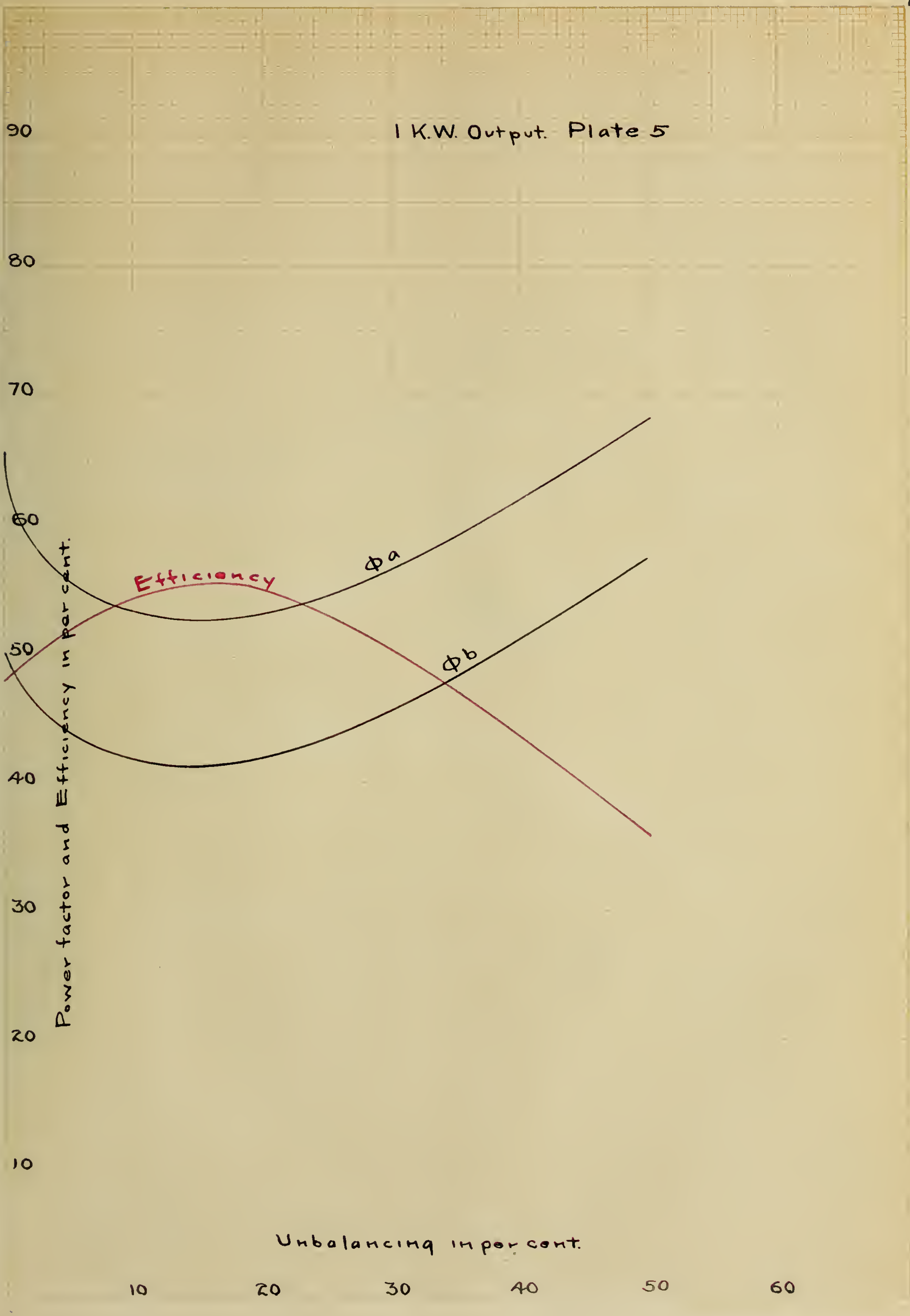
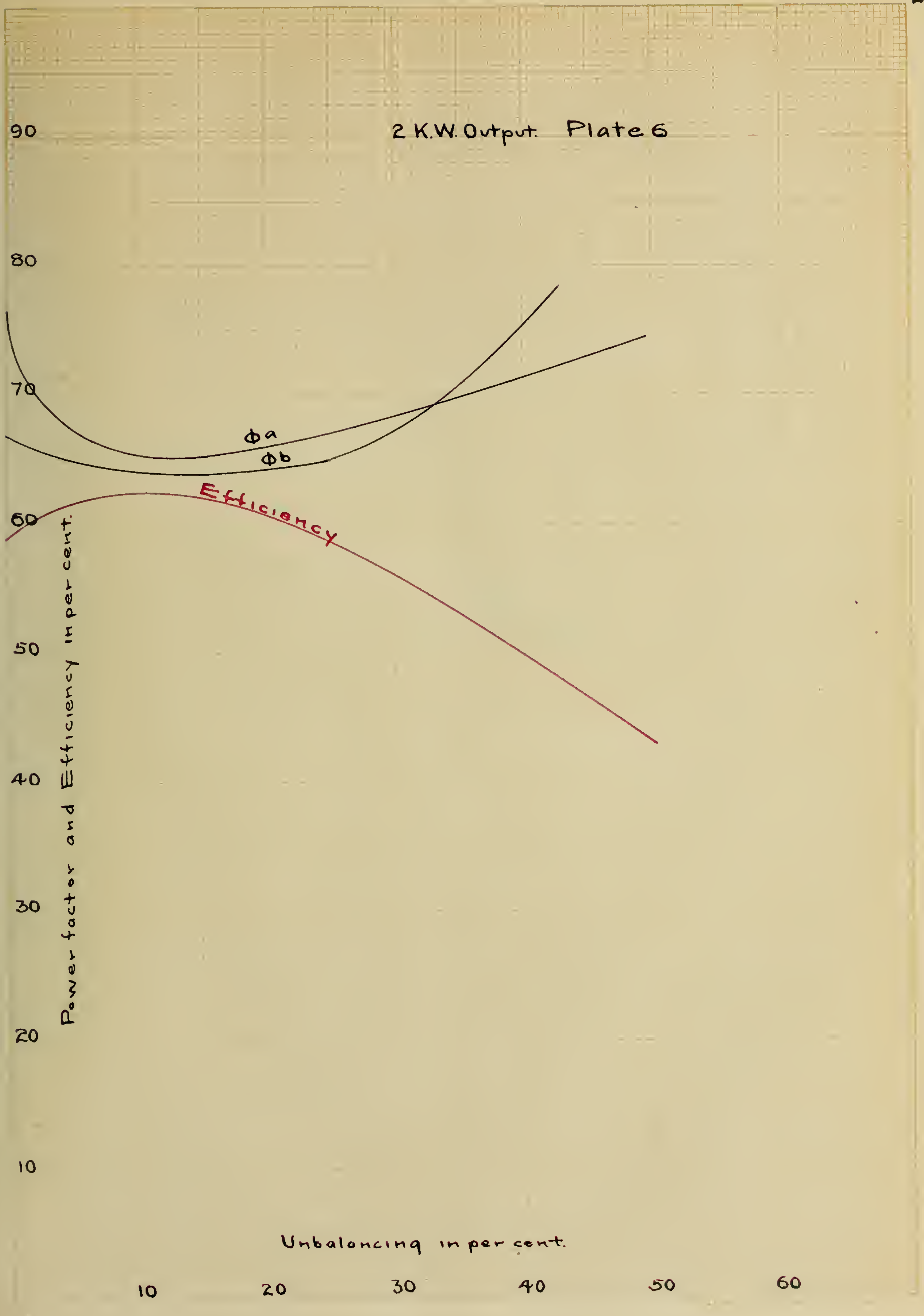
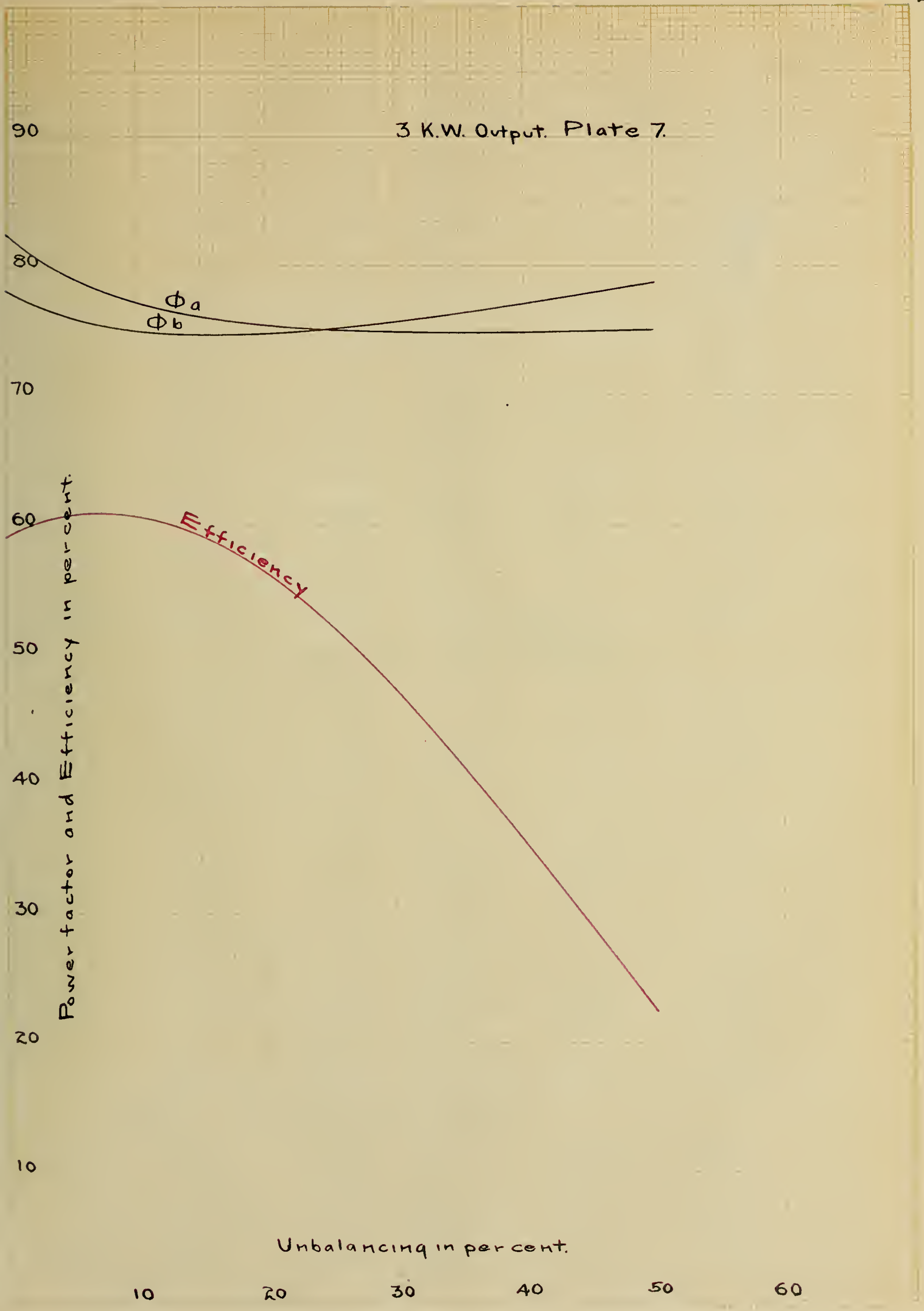


Plate 4a
Percent slip.
50
40
30
20
10
48%
36%
23%
15%
0%
Output in K.W.
1
2
3
EUGENE DIETZGEN CO., CHICAGO.


1 K.W. Output. Plate 5
Power factor and Efficiency in per cent.
Unbalancing in per cent.
Efficiency
Φa
Φb
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60



2 K.W. Output. Plate 6
90
80
70
60
50
40
30
20
10
Φa
Φb
Efficiency
Power factor and Efficiency in per cent.
Unbalancing in per cent.
10
20
30
40
50
60


3 K.W. Output. Plate 7.
90
80
70
60
50
40
30
20
10
Φa
Φb
Efficiency
Power factor and Efficiency in per cent.
Unbalancing in per cent.
10
20
30
40
50
60

Observed Data--- Table 2.

Synchronous Motor. 0% Unbalanced.

Ea volts.	Ia amperes.	Pa K.W.	Eb volts.	Ib amperes.	Pb K.W.
226.0	5.0	.70	228.0	5.0	.50
226.0	7.0	1.10	228.0	6.0	.90
227.0	8.0	1.40	227.0	7.0	1.20
228.0	9.0	1.75	227.0	8.0	1.50
228.0	10.0	2.25	228.0	9.5	2.0
228.0	13.5	2.75	227.0	12.0	2.50
228.0	15.0	3.00	227.0	14.0	2.75
228.0	17.0	3.50	227.0	16.0	3.25
228.0	18.0	3.70	227.0	17.0	3.40
228.0	20.0	4.10	227.0	19.0	3.75

13½% Unbalanced.

232.0	12.0	1.00	200.0	12.0	0.0
232.0	8.0	.75	202.0	8.0	.25
232.0	11.0	1.50	202.0	9.0	.50
231.0	12.0	2.0	200.0	10.0	1.00
230.0	13.0	2.25	200.0	10.0	1.25
230.0	15.0	2.75	200.0	11.0	1.75
230.0	17.0	3.25	200.0	13.0	2.25
230.0	20.0	2.75	200.0	15.0	2.75

22% Unbalanced.

230.0	12.0	1.00	180.0	0.0	0.0
230.0	13.0	1.75	183.0	13.0	0.0
228.0	14.0	2.00	182.0	12.0	.50

22% Unbalanced Continued. Table 2.

Ea volts.	Ia amperes.	Pa K.W.	Eb volts.	Ib amperes.	Pb K.W.
228.0	15.0	2.25	181.0	13.0	.75
229.0	17.0	2.75	182.0	13.0	1.25
227.0	18.0	3.35	180.0	14.0	1.75
227.0	20.0	3.75	180.0	15.0	2.00
		30% Unbalanced.			
231.0	15.0	1.00	160.0	6.0	0.0
230.0	15.0	1.50	163.0	18.0	0.0
229.0	18.0	2.25	163.0	17.0	.25
229.0	19.0	2.75	163.0	17.0	.75
228.0	20.0	3.25	162.0	18.0	1.0
228.0	22.0	3.50	161.0	19.0	1.25
		39% Unbalanced.			
232.0	12.0	1.0	143.0	0.0	0.0
226.0	22.0	2.0	145.0	25.0	-.75
225.0	25.0	2.5	145.0	23.0	-.50
224.0	22.0	3.0	143.0	23.0	0.0
226.0	23.0	3.5	144.0	22.0	.75
222.0	24.0	4.0	141.0	23.0	1.25
222.0	25.0	4.5	141.0	24.0	1.50
		52% Unbalanced.			
232.0	7.0	.75	112.0	0.0	0.0
218.0	20.0	2.00	110.0	30.0	-1.25
220.0	22.0	3.00	110.0	29.5	-.50
221.0	25.0	3.50	111.0	29.0	0.0

52% Unbalanced Continued. Table 2.

Ea volts.	Ia amperes.	Pa K.W.	Eb volts.	Ib amperes.	Pb K.W.
224.0	26.0	4.00	110.0	29.5	.75
222.0	28.0	4.50	108.0	29.0	1.00
220.0	32.0	5.00	106.0	28.5	1.25

Table 2a.

7% Unbalanced.

213.0	13.0	3.2	230.0	0.0	0.0
209.0	17.0	3.5	228.0	5.0	.75
210.0	20.0	4.0	227.0	8.0	1.5
210.0	22.0	4.5	227.0	11.0	2.0
213.0	24.0	5.0	230.0	13.0	2.4
210.0	26.0	5.25	226.0	15.0	2.9
209.0	27.0	5.75	226.0	15.0	3.2
213.0	29.0	6.00	230.0	16.0	3.5
208.0	30.0	6.25	225.0	18.0	3.8

15% Unbalanced.

190.0	13.0	2.55	225.0	0.0	0.0
192.0	16.0	2.5	227.0	6.0	.90
190.0	19.0	3.0	226.0	10.0	1.6
191.0	21.0	3.5	227.0	13.0	2.20
193.0	22.0	3.75	230.0	15.0	2.45
188.0	24.0	4.15	223.0	16.0	2.85
188.0	25.0	4.35	223.0	17.0	3.15
188.0	27.0	4.75	225.0	18.0	3.70
186.0	29.0	5.10	220.0	20.0	4.05

24% Unbalanced. Table 2a.

Ea volts.	Ia amperes.	Pa K.W.	Eb volts.	Ib amperes.	Pb K.W.
170.0	13.0	2.04	224.0	0.0	0.0
174.0	19.0	1.85	228.0	12.0	1.50
174.0	21.0	2.35	228.0	14.0	1.90
167.0	23.0	2.75	220.0	16.0	2.45
167.0	24.0	3.20	220.0	17.0	2.90
170.0	25.0	3.50	223.0	18.0	3.20
166.0	27.0	3.75	218.0	20.0	3.65
164.0	28.0	3.75	216.0	21.0	3.80
165.0	29.0	4.25	217.0	22.0	4.30

33% Unbalanced.

Ea volts.	Ia amperes.	Pa K.W.	Eb volts.	Ib amperes.	Pb K.W.
152.0	13.0	1.65	222.0	0.0	0.0
160.0	22.0	1.50	232.0	15.0	1.50
150.0	24.0	2.00	219.0	17.0	2.20
151.0	25.0	2.25	220.0	18.0	2.70
149.0	26.0	2.65	217.0	20.0	3.30
156.0	28.0	3.00	226.0	21.0	3.70
156.0	25.5	3.25	226.0	22.0	4.20
150.0	30.0	3.70	219.0	24.0	4.60

Calculated Data - Table 2.

Synchronous Motor 0% Unbalanced.

Cos θa	Cos θb	Input K.W.	Output K. W.	Efficiency.
.620	.458	1.20	.89	74.2
.695	.658	2.0	1.78	89.0
.772	.757	2.6	2.35	89.7
.854	.825	3.25	3.07	94.4
.898	.924	4.25	3.79	89.3
.895	.920	5.25	4.80	91.5
.878	.867	5.75	5.17	89.8
.902	.893	6.75	6.05	89.8
.902	.885	7.10	6.55	92.2
.900	.868	7.85	7.13	90.8
		15% Unbalanced.		
.558	---	1.00	.89	89.0
.405	.155	1.00	.89	89.0
.588	.275	2.00	1.78	89.0
.722	.500	3.0	2.44	81.5
.751	.625	3.5	3.04	87.0
.798	.796	4.5	3.98	88.5
.833	.835	5.5	4.60	83.7
.816	.917	6.5	5.54	85.3
		22% Unbalanced.		
.562	---	1.00	.89	89.0
.585	.000	1.75	.89	50.7
.626	.228	2.30	1.99	79.7

22% Unbalanced Continued. Table 2.

Cos θa	Cos θb	Input K.W.	Output K.W.	Efficiency.
.657	.318	3.00	2.66	88.8
.706	.528	4.0	3.38	84.5
.796	.694	5.0	4.25	85.0
.826	.695	5.75	4.69	81.6
		30% Unbalanced.		
.556	---	1.0	.89	89.0
.454	.000	1.5	.89	59.3
.546	.090	2.5	1.99	79.7
.636	.271	3.5	2.65	75.7
.716	.346	4.25	3.39	79.8
.697	.408	4.75	4.00	84.2
		39% Unbalanced.		
.360	---	1.0	.89	89.0
.402	.207	1.25	.89	71.2
.425	.150	2.0	1.99	99.5
.508	.000	3.0	2.67	89.1
.674	.267	4.25	3.24	76.3
.750	.385	5.25	4.05	77.2
.811	.443	6.0	4.60	76.7
		52% Unbalanced.		
.462	---	.75	.89	----
.458	.379	.75	.89	----
.520	.154	2.5	1.98	79.1
.633	.000	3.5	2.7	77.2

52% Unbalanced Continued. Table 2.

Cos θa	Cos θb	Input K.W.	Output K.W.	Efficiency.
.687	.231	4.75	3.37	71.0
.722	.319	5.5	4.2	76.4
.710	.413	6.25	4.94	79.1

Table 2a/ 7% Unbalanced.

Output K.W.	Pb - Pa K.W.
0.0	3.2
.89	2.75
1.98	2.50
2.92	2.50
3.60	2.60
4.48	2.55
5.08	2.55
6.03	2.50
6.18	2.45

15% Unbalanced.

0.0	2.55
.89	1.60
1.76	1.40
2.69	1.30
2.98	1.30
3.76	1.30
4.29	1.20
5.29	1.05
5.37	1.05

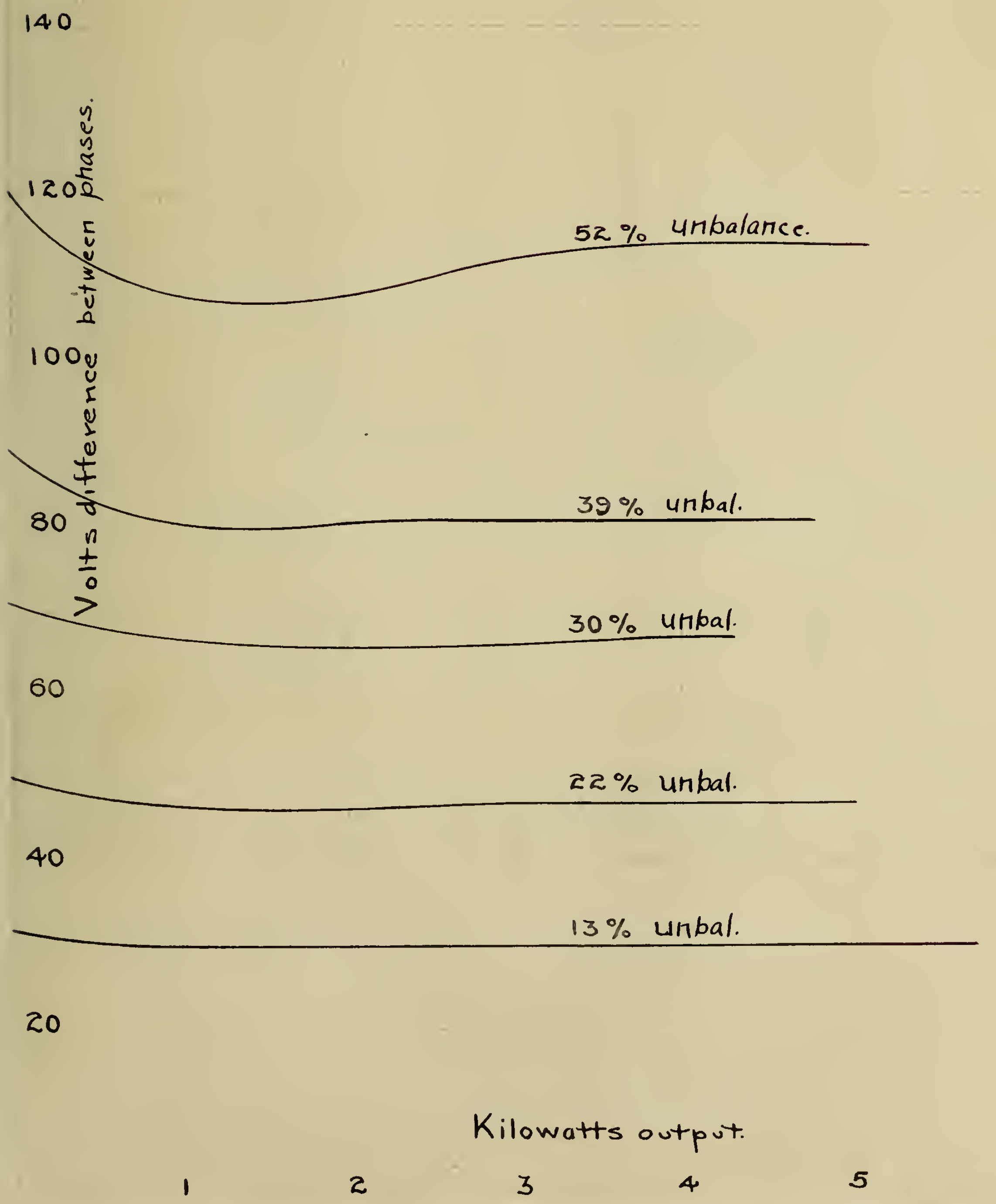
24% Unbalanced/ Table 2a.

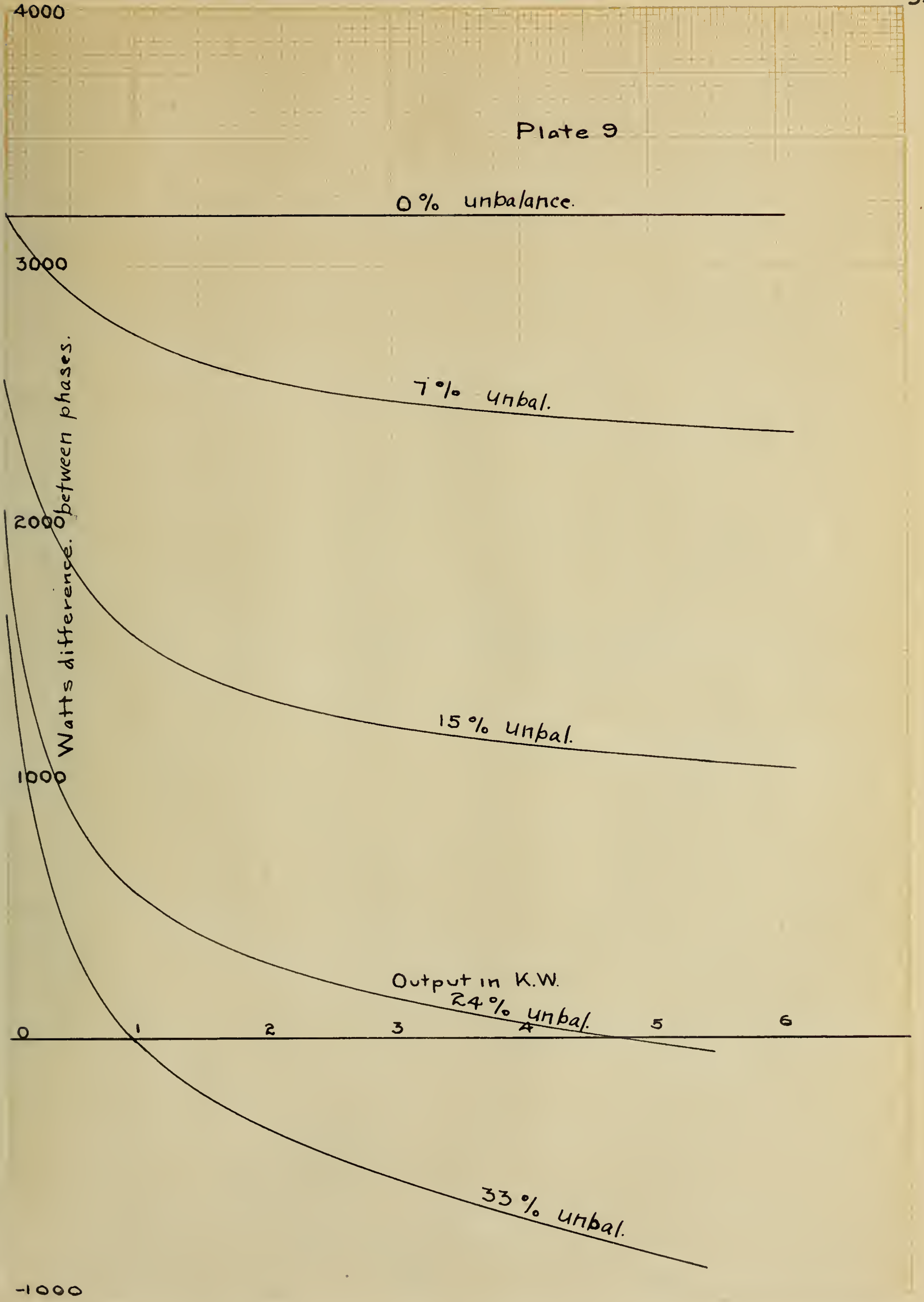
Output K.W.	Pb - pA K.W.
0.0	2.04
.39	.55
1.77	.45
2.67	.50
3.38	.30
3.60	.50
4.42	.10
4.99	-.05
5.31	-.05

33% Unbalanced.

0.0	1.65
.89	0.0
1.83	-.2
2.64	-.15
3.34	-.65
3.63	-.70
4.63	-.95
5.33	-.90

Plate 8


140
120
100
80
60
40
20
Volts difference between phases.
52 % unbalance.
39 % unbal.
30 % unbal.
22 % unbal.
13 % unbal.
Kilowatts output.
1
2
3
4
5
6



4000
Plate 9
0 % unbalance.
3000
7 % unbal.
Watts difference between phases.
2000
15 % unbal.
1000
Output in K.W.
24 % unbal.
0
1
2
3
4
5
6
33 % unbal.
-1000

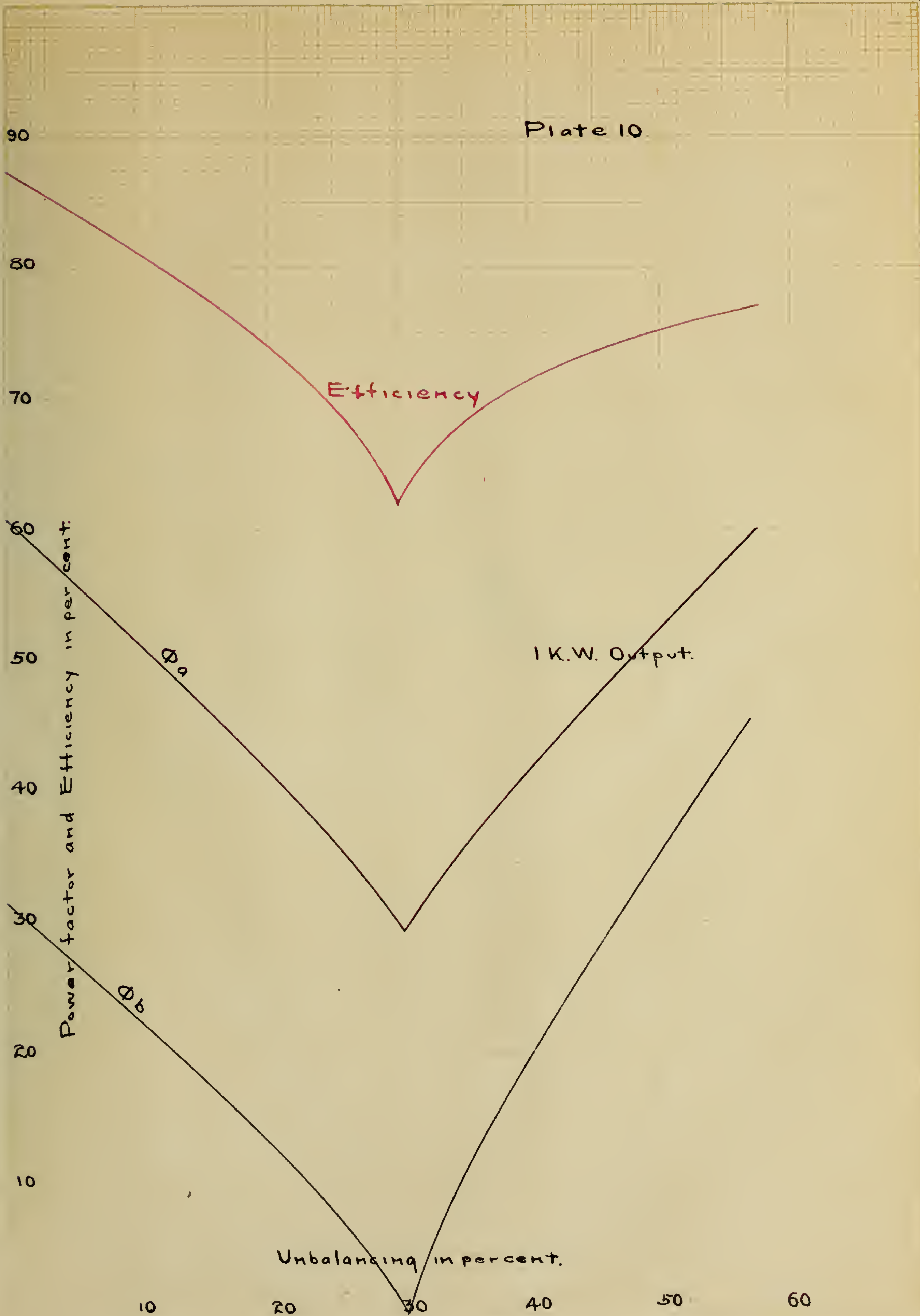


Plate 10
Efficiency
I K.W. Output.
Øa
Øb
Power factor and Efficiency in per cent.
Unbalancing in per cent.
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60

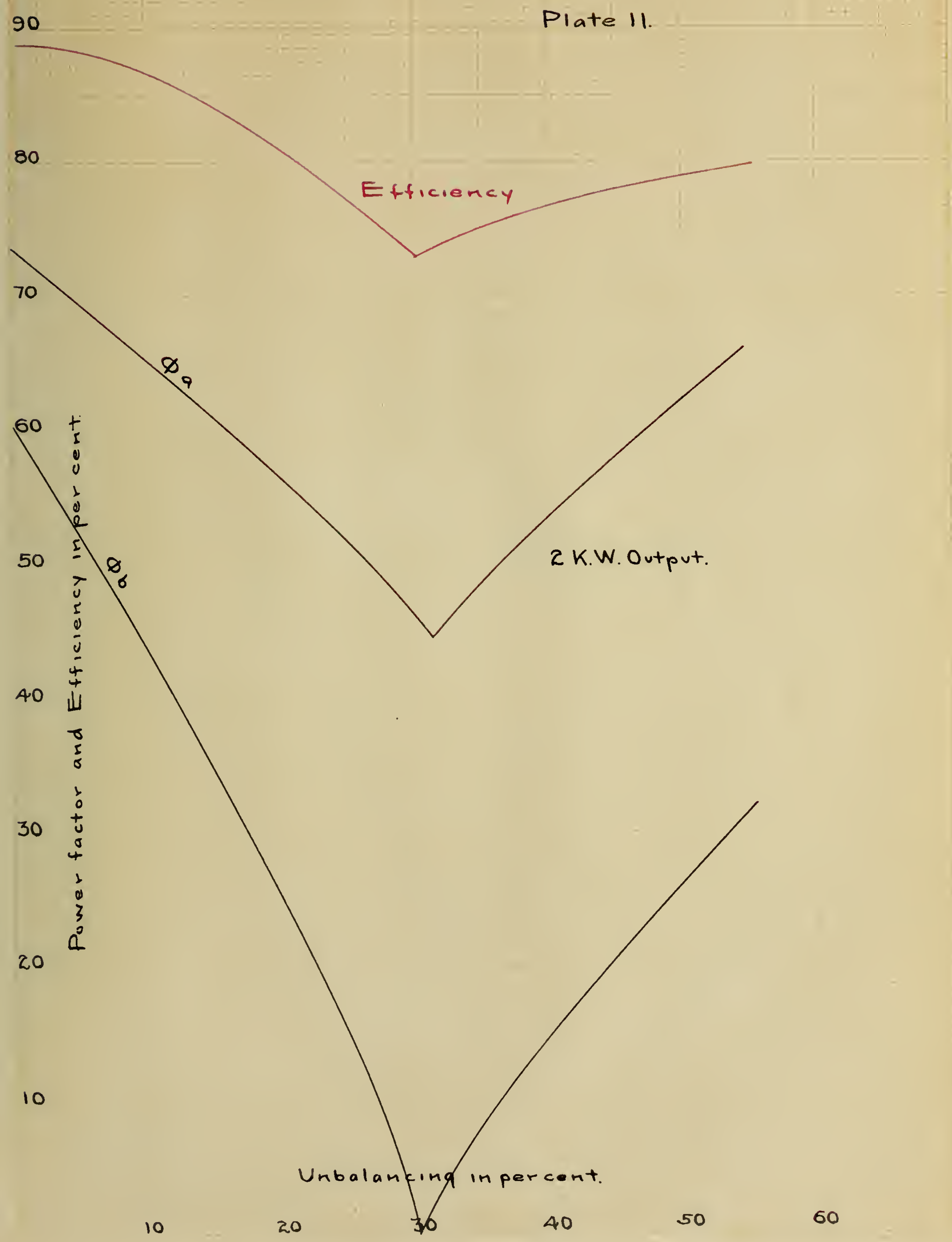


Plate 11.
90
80
70
60
50
40
30
20
10
Efficiency
Øa
Øb
2 K.W. Output.
Power factor and Efficiency in per cent.
Unbalancing in per cent.
10
20
30
40
50
60

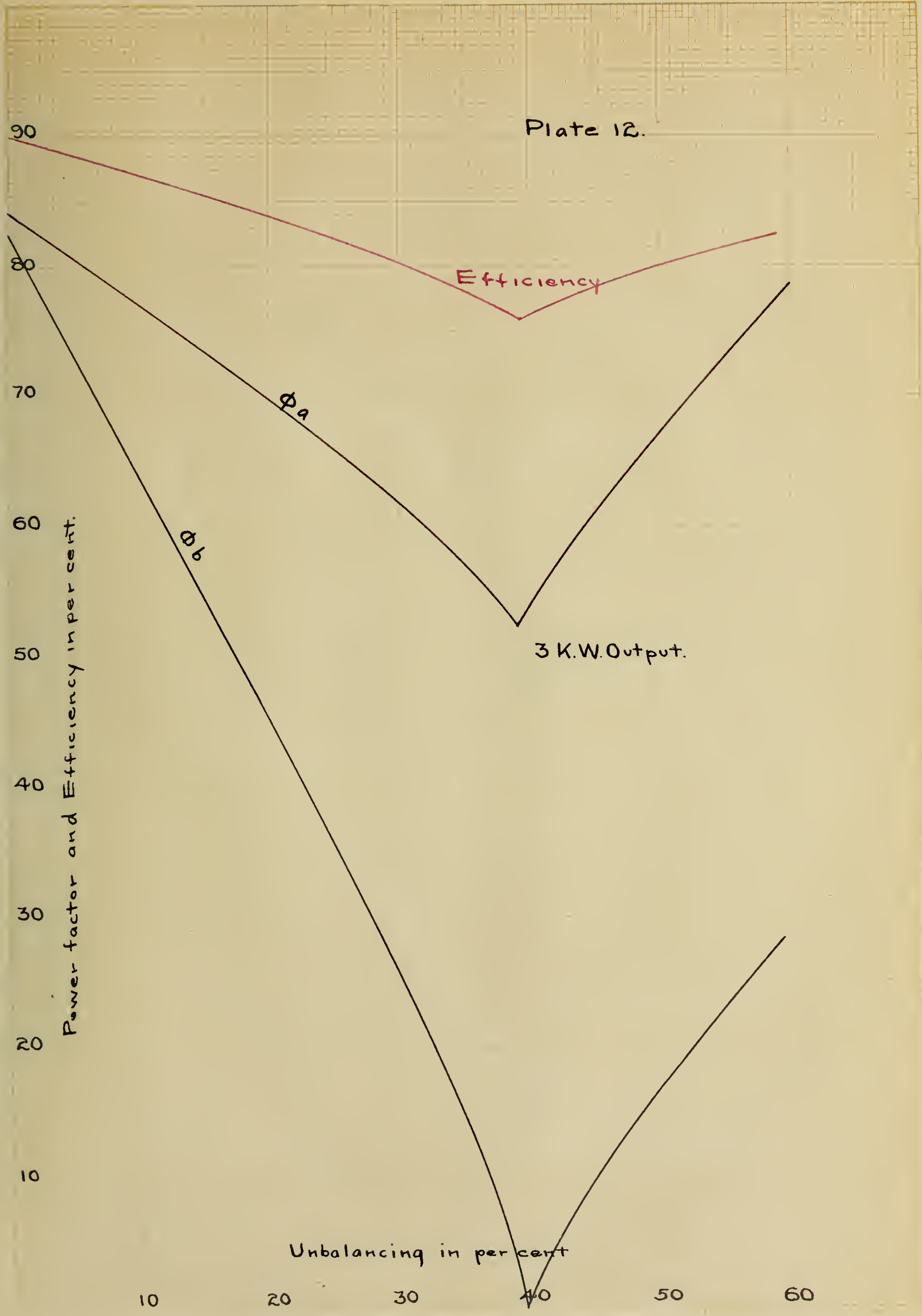


Plate 12.
Efficiency
ϕ_a
ϕ_b
3 K.W. Output.
Power factor and Efficiency in per cent.
Unbalancing in per cent
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60

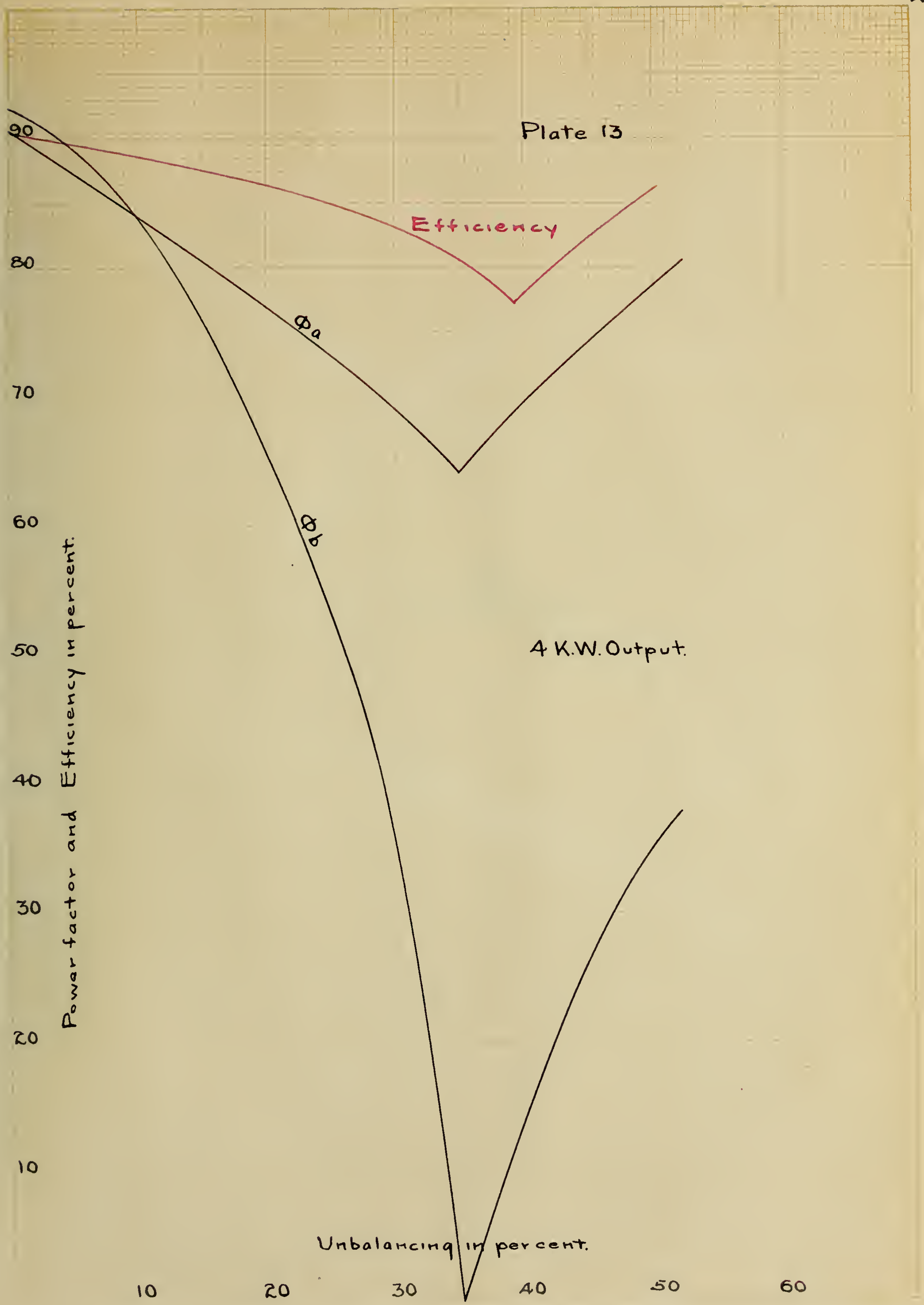


Plate 13
Efficiency
Φa
Φb
4 K.W. Output.
Power factor and Efficiency in percent.
Unbalancing in percent.
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60

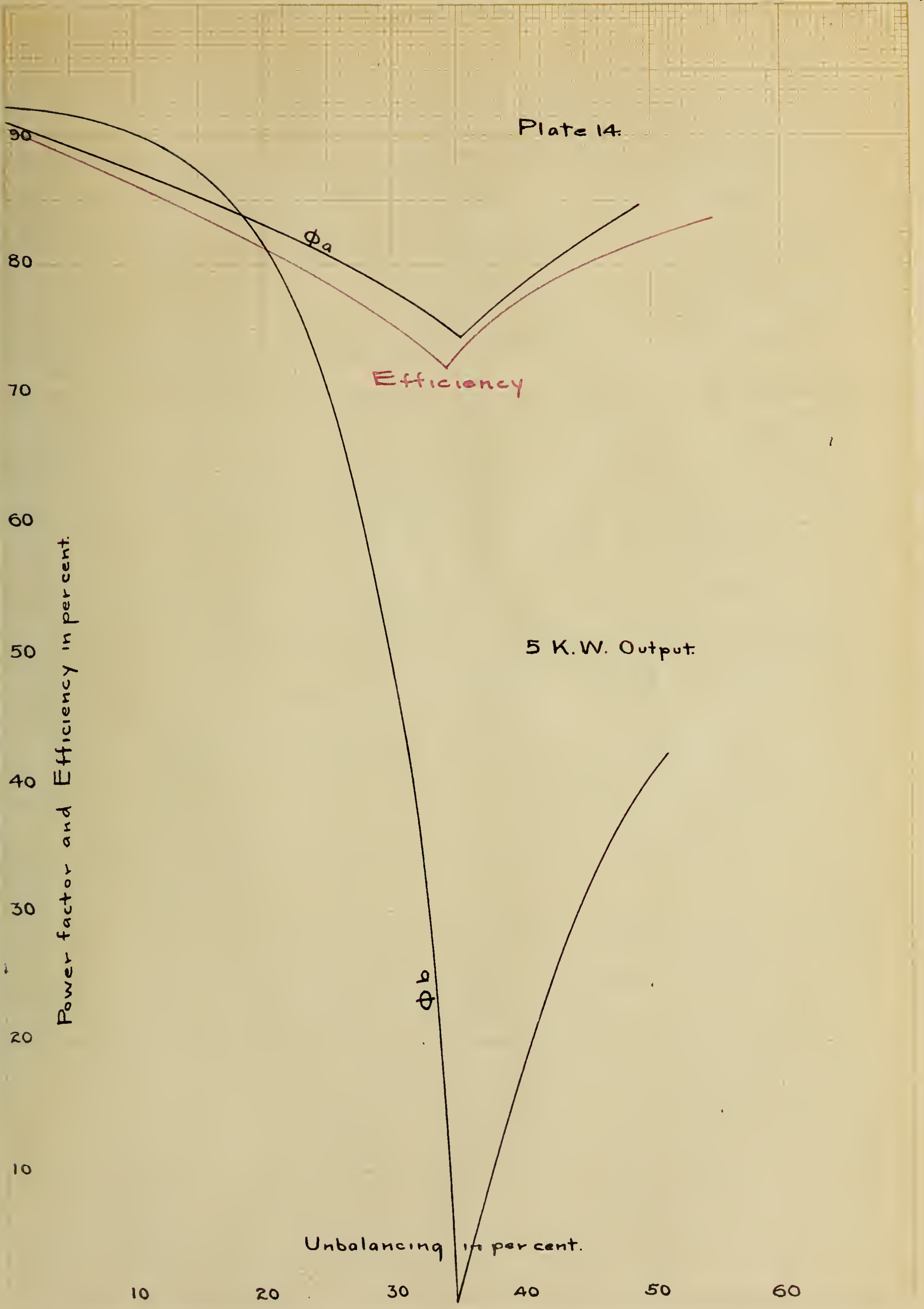


Plate 14.
90
80
70
60
50
40
30
20
10
Φa
Efficiency
Φb
5 K.W. Output.
Power factor and Efficiency in per cent.
Unbalancing in per cent.
10
20
30
40
50
60

Discussion of Data and Curves:

Curves are shown on plate 2 for the induction motor, and on plate 8 for the synchronous machine showing the voltage difference between the phases for different loads. It will be noted that the induction machine was operated at 110 volts, while the other ran from 220 volt mains. The curves are plotted to such a scale however, so that the two sets of data are comparable. It is noticeable that the synchronous machine has a greater balancing effect than the induction machine as was expected. It was found that there was a maximum balancing effect for about 50% load on the induction motor and 25% load on the synchronous machine. Beyond this point the low voltage tends to decrease and gradually falls off up to full load, not coming to its original value however. This does not confirm the conclusion reached by Messrs. Crossett and Hall that the motor did not balance above 33% load. The data taken in this test points to the conclusion that the motor balances for all loads, having a maximum effect however, at the loads mentioned..

On plates 5 to 7 and 10 to 14 are shown curves between power factor in each phase and the efficiency of the motor plotted against per cent of unbalance, separate curves being shown for the different loads. The synchronous machine showed the same characteristics in the low phase as was shown by the induction motor tested by Messrs. Crossett and Hall. That is, the power factor in the low voltage phase gradually decreased as the per cent of unbalance increased, passing through zero between 30% and 40% of

unbalance, and then increasing again. The power factor in the constant voltage phase decreased, with a minimum where the other power factor passed through zero and then increasing as before. The efficiency of the motor had a minimum at a point corresponding to the mimima of the power factors, the natural result of the low power factors.

The induction machine did not behave like the synchronous motor. The power factor in the low voltage phase as shown by the curves in plates 5 to 7 , did not fall to zero but had a minimum at a point corresponding to the zero point on the synchronous machine. The minimum in either phase was not so pronounced as in the case of the synchronous machine and corresponded to a maximum in the efficiency curve at the same per cent unbalancing. The fact that a maximum in the efficiency of the induction machine occurred at the same point as a minimum in the efficiency of the synchronous machine is worthy of mention. It may be explained by a consideration of the efficiency curves of the two machines balanced. The efficiency curve for the synchronous machine plotted between efficiency and kilowatt output is nearly horizontal, and therefore efficiency plotted against per cent of unbalance for this machine will be concave upwards and have a minimum at the point of minimum power factor due to the large I^2R losses and core losses for the heavy curents at low power factors. The efficiency curve for the induction machine, plotted against kilowatt output has a decided maximum at about 50% load and this maximum

predominates over the tendency of the motor to have lower efficiency at low power factors making the curves in plates 10 to 14 concave downwards.

On plates 8 and 9 are shown curves between watts difference between the two phases and kilowatt output. The lamp load which caused the difference in power at zero load was placed on the low voltage side and as the load became greater, the lamp load was taken by the high voltage side, the amount of balancing effect reaching a maximum as in the case of the unbalanced voltage. With a very bad unbalance the difference in watts became negative as soon as the motor was thrown on the line, that is the high voltage side carried the lamp load. As before, the synchronous machine was more effective in balancing than the induction machine.

Conclusion.

In conclusion it would seem that the balancing effect on the voltage is not sufficient to be worthy of consideration and not of commercial importance. The balancing effect is only of much effect when the unbalance is severe, which would not be obtained or allowed in practice. It does seem however, the the balancing effect on the power is of use on a commercial scale. Suppose lamps and motors both are connected on a polyphase system. If the lamp load becomes excessive on any one phase the voltage will fall on that phase due to the IR drop of the line. The other phases will then assume part of the load and tend to equalize the load on the generator.

It should be remembered in considering the results obtained,

that the data was very hard to get. Due to the interchange of power between the phases, the instruments' pointers varied between wide limits, the variation amounting to 200% or 300% for the low readings. This fact makes the data obtained, for small loads especially, rather uncertain and subject to comparatively large errors.